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ELECTRONIC MASKING FOR TELECINE: A REVIEW OF MASKING FOR POSITIVE AND NEGATIVE FILM

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Summary

This Report reviews the theory of electronic masking for telecine for use with positive print, negative and reversal films. Practical results are discussed and it is concluded that satisfactory results can be obtained for positive print and negative films from the theory of electronic dye masking. Reversal films, because of the magnitude of their interimage effects do not give good results with this type of masking. A satisfactory mask was calculated for reversal film from measurements of the response of a typical telecine to samples of known exposure.

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1. Introduction

This Report is intended to be read in conjunction with a previous Report on telecine masking.[1] It derives theories of electronic masking for telecine that can be applied to both positive and negative films.

There are two distinct approaches to the problem of displaying colour film on television. The more straightforward approach is to reproduce the film exactly as it would appear when projected optically. This is known as the 'as optical' method. Alternatively, the film can be regarded as a three channel recording medium (of red, green and blue separation signals) and the telecine used to recover this information. The second approach is taken here. It has the advantage that it can be used for films which are not intended for optical projection, like camera negatives. It also avoids some of the colorimetric errors introduced by the film.

The theory given here is, however, incomplete. A camera film analyses the scene into its colour components using an analysis which is designed to match the transmission characteristics of the projection film dyes. The dye separation signals are not intentionally best suited to the phosphors of a television display. To avoid the colorimetric errors resulting from this discrepancy the telecine signals are also matrixed with an 'analysis matrix'. The theory and calculation of analysis matrices are described elsewhere.[2]

A major influence on the colour of film images is the interimage effect. This is a processing effect in which there is cross-coupling between the development reactions of the film dyes. The effect is noticeable mainly as an increase in colour saturation which cannot be explained from the spectral sensitivity curves of the emulsion. A theoretical treatment of the interimage effect is beyond the scope of this Report. However, its implications have been investigated and a successful method of dealing with it is described.

2. Electronic masking of telecine signals

Fig. 1 shows the spectral density characteristics of the dyes of a typical colour film. It can be seen that these overlap considerably. This is partly because the choice of dye material is limited by other considerations, such as stability and development rate. However, overlap is essential to produce a sufficiently dense 'black' for optical projection. Otherwise the film contrast would be inadequate. For telecine replay the overlaps are unnecessary and make any colour analysis suffer from crosstalk. A change in cyan density for example will be detected by the blue and green channels as well as by the red channel.

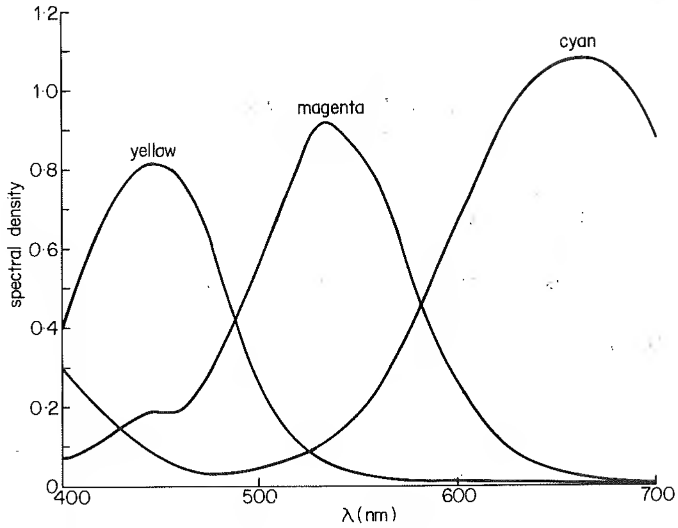

Fig. 1 - Typical 'neutral set' of film dye characteristics

The crosstalk can be removed, to a first approximation, by matrixing the telecine signals. This is called electronic 'masking' by analogy with a technique of making photographic 'masks' to enhance the saturation of colour prints (see Section 5.1).

3. Film scanning by telecine

3.1. The photomultiplier output signals

The photomultipliers in a flying-spot telecine provide signal currents in proportion to the total light energy they receive. In a colour telecine the light from the flying-spot tube is passed through the film, split into red, green and blue components by dichroic mirrors, and collected by three separate photomultipliers.

The colour analysis is calculated by multiplying together the spectral characteristics of all the components in the particular light path. This consists of the spectrum of the light emitted by the flying-spot tube, the transmission and reflection coefficients of the dichroic mirrors and the spectral response of the photomultiplier.

With no film in the gate the output of a photomultiplier is:

$$V_{OG} = K\int_0^\infty T_s(\lambda)d\lambda \tag{1}$$

where $T_s(\lambda)$ is the telecine analysis for the particular

channel and K is a constant related to the photomultiplier gain.

When film is placed in the telecine gate is absorbs some of the light falling on it and the photomultiplier output falls. Since the photomultiplier responds linearly to changes in incident energy its output becomes:

$$V_f = K\int_0^\infty T_s(\lambda)T_f(\lambda)d\lambda \tag{2}$$

where $T_f(\lambda)$ is the transmission of the film.

It is convenient to refer all photomultiplier outputs to the open gate signal, so that V_{OG} is defined as unity. This removes the constant K.

Substituting for K from Equation (1) into Equation (2):

$$V_f = \frac{\int_0^\infty T_s(\lambda)T_f(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{3}$$

$T_f(\lambda)$ is the product of the individual spectral transmission characteristics of the cyan, magenta and yellow dyes. If these are represented by $T_C(\lambda)$, $T_M(\lambda)$ and $T_Y(\lambda)$ then Equation (3) can be rewritten:

$$V_f = \frac{\int_0^\infty T_s(\lambda)T_C(\lambda)T_M(\lambda)T_Y(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{4}$$

3.2. The narrow-band analysis approximation

Consider the expression

$$V_f = \frac{\int_0^\infty T_C(\lambda)T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \cdot \frac{\int_0^\infty T_M(\lambda)T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \cdot \frac{\int_0^\infty T_Y(\lambda)T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{5}$$

It will be shown that Equations (4) and (5) are approximately equal if the analysis passband is relatively narrow. If the passband is narrow, so that T_C, T_M and T_Y vary only slowly across it, the transmission of each dye as a function of wavelength can be replaced in the above equations by a 'mean' value. Let these 'mean' values be $\overline{T}_C$, $\overline{T}_M$ and $\overline{T}_Y$ for the cyan, magenta and yellow dyes respectively. Since these are constants they may be taken outside the integrals and further simplifications become possible.

From Equation (4)

$$V_f = \frac{\int_0^\infty T_s(\lambda).\overline{T}_C.\overline{T}_M.\overline{T}_Y d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{6}$$

or

$$V_f = \overline{T}_C\overline{T}_M\overline{T}_Y \tag{7}$$

From Equation (5)

$$V_f = \frac{\overline{T}_C\int_0^\infty T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \cdot \frac{\overline{T}_M\int_0^\infty T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \cdot \frac{\overline{T}_Y\int_0^\infty T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{8}$$

or

$$V_f = \overline{T}_C\overline{T}_M\overline{T}_Y \tag{9}$$

which is identical to Equation (7). Equations (4) and (5) are therefore equivalent if the transmission of each dye varies sufficiently slowly over the analysis passband. This is approximately true for practical telecine analyses.

Comparison of Equations (5) and (7) show the method which should be used to calculate the 'mean' values $\overline{T}_C$, $\overline{T}_M$ and $\overline{T}_Y$.

$$\overline{T}_C = \frac{\int_0^\infty T_C(\lambda).T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{10}$$

$$\overline{T}_M = \frac{\int_0^\infty T_M(\lambda).T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \tag{11}$$

$$\overline{T}_Y = \frac{\int_0^\infty T_Y(\lambda).T_s(\lambda)d\lambda}{\int_0^\infty T_s(\lambda)d\lambda} \qquad (12)$$

Density is defined by the expression

$$D = -\text{Log}_{10} T \qquad (13)$$

Let $\overline{D}_C$, $\overline{D}_M$ and $\overline{D}_Y$ be the 'mean' densities of the three dyes defined by the equation:

$$\overline{D}_C = -\text{Log}_{10} \overline{T}_C \qquad (14)$$

with similar equations for $\overline{D}_M$ and $\overline{D}_Y$.

From Equation (9)

$$-\text{Log}_{10} V_f = \overline{D}_C + \overline{D}_M + \overline{D}_Y \qquad (15)$$

The densities of film dyes can also be expressed as equivalent neutral densities, or E.N.D.s. The E.N.D. of a dye is the density that would result if the other two dyes were added in just sufficient quantities to make a visual neutral. If coefficients a_1, a_2 and a_3 relate the mean densities to the equivalent neutral densities, D_C, D_M and D_Y then

$$\overline{D}_C = a_1 D_C \qquad (16)$$

$$\overline{D}_M = a_2 D_M \qquad (17)$$

$$\overline{D}_Y = a_3 D_Y \qquad (18)$$

then Equation (15) becomes

$$-\text{Log}_{10} V_f = a_1 D_C + a_2 D_M + a_3 D_Y \qquad (19)$$

where $$a_1 = \frac{\overline{D}_C}{D_C} = \frac{-1}{D_C} \text{Log}_{10} \left[\frac{\int_0^\infty T_C(\lambda) T_s(\lambda) d\lambda}{\int_0^\infty T_s(\lambda) d\lambda} \right] \qquad (20)$$

with similar equations for a_2 and a_3.

3.3. The dye-masking equation

Equation (19) was developed for a single analysis channel. Extending it to the red, green and blue channels gives the equation:

$$\begin{bmatrix} -\text{Log}\, V_R \\ -\text{Log}\, V_G \\ -\text{Log}\, V_B \end{bmatrix} = \begin{bmatrix} a_{1R} & a_{2R} & a_{3R} \\ a_{1G} & a_{2G} & a_{3G} \\ a_{1B} & a_{2B} & a_{3B} \end{bmatrix} \begin{bmatrix} D_C \\ D_M \\ D_Y \end{bmatrix} \qquad (21)$$

where V_R, V_G and V_B are the photomultiplier output signals.

This equation can be written more simply as a transformation of one three-dimensional vector (whose co-ordinates are the equivalent neutral densities of the three dyes) into another (of the logarithmic photomultiplier outputs). The 'transformation' matrix in Equation (21) is called the crosstalk matrix.

The equation can be rewritten

$$-\text{Log}_{10} \mathbf{V} = \mathbf{AD} \qquad (22)$$

where $\mathbf{D}$ is the equivalent neutral density vector and $\mathbf{V}$ is the photomultiplier output vector.

Transposing:

$$\mathbf{D} = -\mathbf{A}^{-1} \text{Log}_{10} \mathbf{V} \qquad (23)$$

Equation (23) is the masking equation. It shows that the equivalent neutral densities of the film can be recovered by linear matrixing of the logarithmic photomultiplier signals. Many telecines already have logarithmic signal amplifiers following the photomultipliers as the first stage of gamma correction. This type of masking is therefore particularly suited to these machines.

4. Calculation of the masking matrix

The film manufacturer usually gives the dye data in graphical form, showing the spectral densities of each dye in a neutral dye set at a given density. Equation (20), which is the formula for the calculation of the crosstalk matrix, implies that the matrix is independent of density. This is not exactly so, because the narrow-band analysis approximation becomes increasingly inaccurate at higher densities. However, with a typical telecine analysis, increasing the density from 0·1 to 2·5 changes the terms of the matrix by typically only 0·03.

A computer program was written to calculate the mask coefficients. The integrals were replaced by summations at evenly spaced discrete wavelengths across the visible band. The range 400 to 750 nm, covered in 10 nm steps, was found to be sufficient.

5. Further considerations

5.1. Masking for negative film

The preceding theory cannot be applied to negative film as it stands, for two reasons. Most negative films contain more than three dyes. Extra dye images, called masks, are produced to compensate for overlaps in the absorption characteristics of the main dyes. In some Graphic Arts procedures these mask images are made separately, by taking low contrast prints from the negative. These prints are then laid, like a mask, over the negative in the printer. In current negative films the masks are an

integral part, and are produced automatically when the film is developed. Electronic 'masking' is so called because it is used for the same purpose, to improve the saturation of the final image.

Secondly, the density of a negative film dye is not specified as an equivalent neutral density, because negative film is not designed for direct viewing. There is no reason for a negative to maintain the colour balance of neutrals in the original scene. In particular, masked negatives usually have a considerable overall colour cast, and visual greyscale tracking is not maintained. These errors are corrected by complimentary characteristics in the print film.

A masked negative still behaves like a three-dye film because each mask is 'coupled' to just one main dye. The coupling is inherent in the processing and is such that the two dyes are produced in complementary quantities. The nett result is a variable dye, equal to the 'difference' between the mask and main dye, and a fixed dye, equal to the densest mask that can be produced. The set of variable dyes, called equivalent dyes, is usually quoted by the manufacturer, together with the total fixed dye, in the specification of the film.

The equivalent dye data can be used in the masking theory in place of the normal dye data. The fixed component acts like a filter in the optical path, and it can be included as if it were part of the telecine analysis.

The matrix cannot yet be calculated because the equivalent neutral densities cannot be specified. As a first approximation a matrix is calculated with 'plausible' E.N.D. values. These values can be found from the equivalent dye spectral density curves by regarding them as applying to a print or reversal film. This matrix will remove crosstalk but will give the dye densities of the film in arbitrary units, so that the greyscale tracking is incorrect.

The greyscale tracking is corrected by making measurements on a practical telecine with a negative greyscale in the gate. This greyscale should be chosen from a number, processed at different times, so that the correction is calculated for representative processing conditions. The greyscale tracking is corrected by scaling each row of the matrix to make the red, green and blue logarithmic signals equal. The whole matrix is then scaled to give the preferred picture gamma.

5.2. The analysis matrix

A small further improvement to telecine pictures is possible with an analysis matrix. With dye-masking alone the telecine output signals are proportional, ideally, to the cyan, magenta and yellow dye signals recorded on the film. These signals are determined by the film analysis, which is not in general well matched to television phosphors.

The telecine analysis matrix is similar to those used in television cameras, and its calculation is described in detail elsewhere.[2] The result is a compromise as it is impossible to correct completely for analysis errors with a linear matrix.

The matrix is best applied to signals which are proportional to scene brightness. However, unless a unity gamma film has been used, such signals do not exist anywhere in the chain. The analysis matrix is therefore combined with the masking matrix, where it operates on logarithmic signals. In practice the additional errors incurred are small because the analysis matrix is close to a unity matrix, and because it can be optimised for use on logarithmic signals.

5.3. The interimage effect

The interimage effect[3,4] is cross-coupling between the dye development reactions in the processing of the film. It is caused by byproducts of these reactions, which are capable of slowing down further development and diffusing a short distance through the film, inhibiting the development of the other dyes. The result is an increase of colour saturation, and a shifting of certain hues. The effect is present to some extent in all multilayer colour films, in some cases being deliberately enhanced to improve the colour rendition.

The interimage effect is difficult to predict and its theoretical treatment is beyond the scope of this Report. It can however completely change the colorimetry of the telecine replay because it destroys the simple relationship between the exposure and density of each dye.

5.3.1. The interimage effect in negative film

A masking matrix was calculated for the direct replay of negative film, using the method described in Section 5.1. The resulting pictures were very over-saturated in red areas and slightly over-saturated in blue areas. This was corrected by multiplying the mask by a desaturating matrix of the form

$$\begin{bmatrix} 1-2x & x & x \\ 0 & 1 & 0 \\ y & y & 1-2y \end{bmatrix}$$

The green saturation was not changed.

The pictures were improved considerably by this modification. Small errors were still noticeable on good reference colours such as grass or flesh-tones, although they were not disturbing. They could probably be removed by slight adjustments to the desaturation matrix. This matrix has symmetrical rows, whereas in practice the interimage effect tends to be greater between adjacent dyes. (The order of the dyes in the emulsion is cyan, magenta, yellow, corresponding to the red, green and blue images respectively.)

5.3.2. The interimage effect in print film

Strictly, masking for print films should take into account the crosstalk incurred in printing from the negative. However, if this is done the pictures are again oversaturated. Better pictures are obtained if the printing crosstalk is ignored. This is to be expected : the positive-negative

system is designed to give good colour quality prints, using the interimage effect in both films to cancel the print crosstalk not already removed by dye masking.

5.3.3. The interimage effect in reversal film

The interimage effect is enhanced in reversal films so that it can be used alone to maintain colour saturation. It would be impractical to use dye masking for this purpose. Reversal film is designed for direct projection and the colour cast of the mask would be unacceptable.

An electronic mask for reversal film calculated from the dye characteristics alone therefore gives pictures of extremely high saturation, as expected.

The colour saturation was initially restored to a reasonable level, using a matrix with symmetrical rows, but the colour rendering was still unsatisfactory. This was because the interimage effect is large enough in reversal film for its asymmetry to be noticeable. Asymmetry in this context means that each dye does not influence the other two dyes equally.

6. Calculation of a mask for reversal film

A theoretical derivation of a mask for reversal film would involve a mathematical model of the interimage effect. A more direct method is to measure test samples of film in a telecine, and to calculate a mask from these measurements.[5]

Samples of reversal film were exposed to a red, a green and a blue light source in eight combinations of a high and low exposure level for each colour to produce a set of 'colour-bars'.* The processed film was scanned in a flying-spot telecine and the photomultiplier outputs measured for each colour. As the original exposure of the film was known the total crosstalk, including the interimage effect, could be calculated.

The saturation of the colour-bars that are recorded on the film should be high enough to allow accurate measurement of the telecine signals in the presence of photomultiplier and other noise. However, it should also be low enough to ensure that the film dyes are not over- or under-exposed. The bars used in this investigation had a ratio between 'high' and 'low' exposures of each colour of approximately 8·2 : 1. This corresponds to a logarithmic exposure range of approximately 0·9.

Tungsten lamps filtered with narrowband colour filters were used to expose the film. Narrowband filters were used to minimise the crosstalk, which was estimated to be, in the worst instance, only a few precent. However it was allowed for in the calculations.

The colour-bars used were the primary additive and subtractive colours, together with light and dark grey, eight colours in all. Measurements were made at the photomultiplier outputs to avoid errors introduced by minor deviations in the laws of the logarithmic amplifiers. The signals were converted to logarithmic form by calculation.

Let $\mathbf{M}$ represent the correction matrix, with dimensions 3 x 3. Let $\mathbf{A}$ represent the logarithmic telecine signals for all eight colour-bars, written as a 3 x 8 matrix. Let $\mathbf{B}$ represent a corresponding 3 x 8 matrix of the logarithmic exposures of the colour-bars.

Assuming that the interimage effect, the dye crosstalk and the transfer characteristics of the film are linear in loargithmic space:

$$\mathbf{B} = \mathbf{MA}$$

This equation cannot be solved simply for $\mathbf{M}$ because $\mathbf{A}$ is a non-square matrix and has no inverse. This is because the equation represents 24 linear simultaneous equations containing a total of only nine unknowns, the terms of $\mathbf{M}$. If the assumptions stated above were perfectly true, and the measurements had been made with no error, the 24 equations would degenerate into nine independent equations, with a unique set of solutions for $\mathbf{M}$. Because the assumptions are not completely fulfilled the equations will be independent, and any solution will be a compromise.

The optimum solution is given by:

$$\widetilde{\mathbf{M}} = \left[[\mathbf{A}\widetilde{\mathbf{A}}]^{-1} . \mathbf{A} \right] \widetilde{\mathbf{B}}$$

where $\widetilde{\mathbf{M}}$ is the transpose of $\mathbf{M}$, etc.

(Note that this equation would simplify to $\mathbf{M} = \mathbf{BA}^{-1}$ if $\mathbf{A}$ and $\mathbf{B}$ were square.)

There is an advantage in using a complete set of colour bars instead of the mathematical minimum of three colours. The colour gamut of the film is more fully explored and non-linearities, especially in the interimage effect, are averaged.

The crosstalk matrix was combined with an analysis matrix to form the complete mask. This was tested with a selection of typical film. A small greyscale correction was needed in the green channel. This is probably because the processing conditions were not completely typical when the samples were made. Small changes were also made to three of the terms because flesh tones had a magenta bias and were too saturated. This was probably caused by non-linearities in the interimage effect.

The final mask produced pictures of good quality from most samples of well exposed film. Where film of uncertain quality must be used a desaturated version of the normal mask gives more consistent results, at the expense of loss of saturation.

7. Conclusions

The calculation of electronic masks for telecine has been described for three types of film in common use.

* This work was done by Kodak Ltd.

The theory of dye-masking gives good results with positive print film. However, this theory does not take into account the interimage effect, which is present to some extent in all types of film. In the negative/positive print system the interimage effects are largely cancelled by crosstalk in the printing. Using a dye-mask with negative or reversal-original film produces oversaturated pictures.

The dye-mask for negative film can be adjusted slightly on typical pictures to yield satisfactory results. In reversal film the interimage effect is larger and it also causes hue changes. Simple arbitrary adjustments to the reversal dye mask are not sufficiently effective.

A mask which gives good results with reversal film can be calculated measuring the response of a typical telecine to a set of filmed test colours.

8. Acknowledgement

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